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THESIS

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by

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ABSTRACT

An investigation is made of the feasibility of the use of the S/N Fatigue Life Gage as a monitoring device for cumulative fatigue damage in 70-30 copper-nickel.

The study is aimed at verifying the hypothesis that the permanent change in resistance experienced by such a gage when bonded to a structure subjected to varying load conditions is a function of the strain history of the underlying material, and that the total resistance change in the gage at the time of crack initiation in the structure is essentially constant, independent of strain level or history.

In particular, because of its importance in naval applications, the material for which this hypothesis has been examined in this study is 70-30 copper-nickel.

The hypothesis is sufficiently well verified to justify recommending testing at additional strain levels, and evaluating the effects of block-cycling, aging and other influences likely to be encountered in in-service monitoring of fatigue damage.

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SYMBOLS AND ABBREVIATIONS

CPM	Cycles per minute
°F	Degree Fahrenheit
G.F.	Gage factor
in.	Inch
ksi	1000 pounds per square inch
N	Number of load cycles
N_o	Number of load cycles to crack initiation in the specimen
R_g	Gage resistance, ohms
ΔR	Resistance change, ohms
α	Measured distance between centerline of S/N gage and centerline of reduced area of specimen, in.
σ'	Measured distance from edge of clamping block to centerline of S/N gage, in.
ϵ_N	Indicator null strain reading, microstrain*
ϵ_c	Compressive strain, microstrain
ϵ_t	Tensile strain, microstrain
ϵ_T	Total strain range, microstrain
ϵ_R	Cyclic strain, zero-to-peak, microstrain
"	Inch
#	Number

*A unit of strain equal to 10^{-6} in./in.

ACKNOWLEDGEMENT

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Many thanks are also due the following people whose helpful interest and technical advice contributed to this investigation: Mr. R. J. Whitehead, Micro-Measurements, Inc., Mr and Mrs. W. T. Bean, W. T. Bean, Inc., Mr. John Hall, Premmco-PH, Inc., and Mr. Michael O'Dea, Naval Postgraduate School.

I. INTRODUCTION

A. BACKGROUND

Volumes have been written on the subject of material failure by fatigue. Laboratory tests have provided much information regarding the nature of fatigue failures, but there has remained a noted lack of a device to measure fatigue damage in a reliable and efficient manner outside of the laboratory.

During the past 30 years, many attempts have been made to measure cumulative fatigue damage in a structure. X-ray diffraction, ultrasonic devices, and destructive type testing represent several methods that are successful only under laboratory conditions [Ref. 3, 5]. Another method of measurement that has been investigated is the attachment of small devices to the structure; for example, foil, wire, or notched tensile members with known fatigue lives bonded to a test structure [Ref. 1]. It has not been possible to continuously monitor fatigue damage with any of the above methods.

While investigators were attempting to develop a useable fatigue-measurement device, users of foil strain gages in fatigue environments were being irritated by a "zero shift" in their gages. Studies of strain gages subjected to fatigue revealed that there was an increase of resistance in these gages. Various additional studies attributed this resistance change to several causes among which were:

1. hairline cracks in the sensing elements;
2. soft gage backings;
3. strain hardening effect on resistivities of materials [Ref. 3].

A result of this work has been the development of the S/N* Fatigue Life Gage by Mr. Darrel R. Harting of the Boeing Company, Seattle, Washington [Ref. 2].

B. THE S/N FATIGUE LIFE GAGE

1. General Description

The S/N Fatigue Life Gage is a small, bondable resistance sensor that resembles the conventional foil strain gage in construction and geometry. It is made of a specially treated constantan foil grid which is encapsulated in a glass-fiber/epoxy laminate. A range of different sizes is available with each size having either integral solder turrets or leads. Bonding techniques are essentially the same as those for conventional strain gages.

The gage is intended to be mounted on a structure at a point where the principal fatigue damage will occur. So mounted, the gage accumulates an irreversible resistance change as damage progresses in the structure. As this resistance change is permanent and irreversible, instrumentation need not be continuously connected during operation. In fact, monitoring can be accomplished by periodically connecting such simple instruments as an ohmmeter or Wheatstone bridge to obtain resistance readings.

Initial resistance of this gage is 100 ohms, and the nominal gage factor is 2.04. Resistance changes occurring at crack initiation in the specimen are generally between two and eight ohms [Ref. 11].

As with any precision measuring device, successful use of this gage is dependent upon intelligent application, meticulous care in installation, and careful measurement of gage output.

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*Trademark: Micro-Measurements, Inc., Romulus, Michigan

2. Gage Properties

The S/N Fatigue Life Gage responds to strain, temperature, and fatigue. It can be used as a conventional strain gage with an initial gage factor of 2.04. This gage factor will increase slightly as the resistance change of the gage increases with exposure to fatigue. This increase amounts to a gage factor of 2.07 at a resistance change of three ohms. Beyond the three ohm change, the gage factor will increase more rapidly with increased resistance change, thereby reducing the reliability of the gage as a strain gage.

The S/N gage as presently manufactured is limited to use between the temperatures of 75° and 150°F. Best results are obtained when measurements are made at or near 75°F.

Reference 3 reports that the permanent change in resistance with fatigue of the grid is a function of grid material, grid configuration, physical dimensions, heat treatment, cold-working, and residual stresses in the grid material. Changing these parameters will alter the characteristics of the fatigue gage.

The gage is a directional device in that it must be installed in the direction of maximum principal strain to provide an accurate indication of total damage. This direction may be established by inspection, experimentally through the use of photoelastic coatings, or by use of rosette strain gages.

3. Employment of the Gage

Uses for the gage range from measurement of fatigue damage at a point to an assessment of relative severity of service. For each use, the following must be considered: location and orientation of the gage, size and geometry of the gage, installation procedures, wiring, data collection, and data analysis [Ref. 7].

The basic premise of S/N Fatigue Life Gage monitoring is that the cumulative resistance change registered by the gage is proportional to cumulative damage regardless of the load spectrum. For service life of a material to be predictable, this postulate must be verified for each material in question. A mean value of gage resistance change at crack initiation can be established for each material by conducting a reasonable number of tests at several constant strain amplitudes and, ideally, a number of tests where the gage is subjected to more than one strain level during a single test. To insure suitability of the gage for use on a material, this change of gage resistance at crack initiation should be fairly constant (e.g., within 10% of the calculated mean) as well as independent of the strain level.

Experience with application of S/N gages to some structural materials indicate that these gages do indeed satisfy the above requirements to an acceptable and useful degree. This thesis, as is stated elsewhere, makes an initial assessment of the suitability of S/N gages for use on an important material which has not been previously examined from this standpoint - namely, 70-30 copper-nickel.

Further developments of the gage and its potential are continuing. Industries such as the automotive, aero-space, and aircraft industries are presently engaged in further investigations of this gage as well as actually applying it on a limited basis in the field. At present, it is considered one of the most accurate devices available for monitoring cumulative fatigue damage of in-service structures [Ref. 1, 3, 5, 8, 9].

An annotated bibliography on the subject of fatigue monitoring is provided in Appendix E. Additionally, other references are listed in the bibliography on page 69.

C. OBJECTIVES

Throughout the Navy, Coast Guard, and Merchant Marine, main sea water piping is predominantly constructed of 70-30 copper-nickel. In particular, in the case of submersibles, these piping systems are subjected to strains exceeding those that piping in a surface vessel would experience.

When the USS THRESHER was lost and opinions were many as to the cause, failure by fatigue of the main sea water piping (70-30 copper-nickel) was high on this list of possible reasons. Though the exact cause of the THRESHER loss was never made public, fatigue in 70-30 copper-nickel became an object of concern in intensive programs intended to improve safety and reliability of undersea and other vessels.

Design of copper-nickel piping systems which are subjected to repeated cycles of strain includes assessment of fatigue life expectancy based upon a postulated number of strain cycles and their intensity and also based upon current information about the fatigue properties of this material.

However, experience indicates first, that actual strain concentration conditions might be somewhat different from those assumed or derived in a theoretical analysis performed during design, and second, that operational use of a vessel after it has been placed in service may be substantially different from the idealized employment which was postulated as a part of the design specifications.

Accordingly, there is always motivation to monitor in-service performance of any such structure so as to detect any likelihood of in-service failure that might not have been adequately indicated by the theoretical analysis which took place during the design state. Most frequently, such monitoring is done by vigorous visual inspection. In some cases, samples may be taken and analyzed, but this involves an expensive repair. Ideally, in-service monitoring would be accomplished in a quantitatively observable

fashion (which did not depend upon visual acuity or highly trained personnel) with minimum interruption to service and with simple and positive equipment. From what has been said about the S/N Fatigue Life Gage in the preceding paragraphs, it is clear that this device offers significant potential for convenient and positive in-service monitoring of fatigue damage. It is evident that there are many structural details of interest in marine construction which are potentially capable of being monitored by use of this device. Because of the fact that there has heretofore been no information available concerning the degree to which the device may be used to obtain accurate evaluation of damage in copper-nickel and because of the great interest there is in this material for marine applications, the investigation reported in this thesis was undertaken with the following objectives:

1. To observe the performance of the S/N Fatigue Life Gage on 70-30 copper-nickel;

2. To accumulate data giving a relation between the change of gage resistance at crack initiation in a 70-30 copper-nickel specimen, the strain level to which the specimen was subjected and the number of load cycles to crack initiation.

3. To determine whether the S/N Fatigue Life Gage offers promise as a monitor of cumulative fatigue damage in 70-30 copper-nickel;

4. To make recommendations for further laboratory investigation with the purpose of assessing the possibilities for a program of routine in-service monitoring of damage to this material in naval applications.

There is particular reason to believe that the application of S/N gages to 70-30 copper-nickel will give a reliable indication of cumulative

fatigue damage. If the base material is one which can sustain an indefinitely large number of low-strain cycles without any damage whereas the gage material does sustain damage at low strain levels, or conversely, then in-service performance of the S/N gage in circumstances where there is appreciable low-strain cycle content to the strain history may lead to incorrect conclusions regarding damage to the underlying structural material. However, in the case of 70-30 copper-nickel we have more than average reason to believe that the base metal performance will be adequately matched by that of the gage which is composed of constantan having a chemical composition of roughly 55% copper, 45% nickel. Thus, we should expect better predictions, using this gage, of damage to 70-30 copper-nickel than we would, say, of damage to mild steel or aluminum. Yet the S/N gage appears, from evidences in the literature, to be successfully applicable to such materials.

II. PROCEDURE

A series of tests were conducted to determine the resistance change registered by the S/N Fatigue Life Gage at crack iniation in 70-30 copper-nickel. Each test and associated specimen were identified by number. The rough data associated with each of these tests may be found in Appendix D. The equipment used in the performance of these tests is described in Appendix B. All specimens were prepared as described in Appendix A.

The specimens were placed in the S/N Fatigue Machine clamping block so that the vertical edge of the longer reduced section coincided with the edge of the clamping block. The horizontal edge of the specimen was positioned 1/8 inch in from the edge of the clamping block. To balance the clamping pressure, the specimen compensating block was placed flush with the other end of the clamping block. All of the tests were reversed bending which necessitated the shim plate being placed on top of the specimen. The positioning of the specimen in the clamping block was carefully checked for each test. Figure 1 shows a specimen in position in the clamping block.

With the specimen secured, the clamping block was placed in one of two positions so as to obtain the desired average cyclic strain amplitude. The clamping block positions designated as positions one and two were the only positions used because position three required shortening of the specimen to avoid interference with the motor.

With the specimen installed and the clamping block positioned as desired, the ambient temperature was recorded. The temperature remained between 75° and 78°F for all tests. For measurements, it was necessary that the specimen be placed in a neutral or reference position. Neutral

position for all measurements was obtained by inserting an Allen wrench in the hole in the cylindrical surface of the flywheel and allowing it to bear against the underside of the belt damper plate. This is roughly indicated by the orientation of an arrow mark on the cam as shown in Figure 2.

An initial gage reading was taken by connecting the S/N Resistance Meter to the gage. This meter was then disconnected with the specimen remaining in neutral position. The Budd/Strainsert Portable Strain Indicator was now connected to the gage and a reading was taken. Any evidence of drift in this reading indicated the possibility of a poor bond between the gage and the specimen surface [Ref. 4]. With no drift, the bond was assumed good and the test proceeded. Next, the Allen wrench was removed and the flywheel was turned by hand so that the test area was in tension and the extreme strain reading was made. By continuing to turn the flywheel, the test area was placed in compression and the other extreme reading was recorded. The specimen was then returned to its neutral position by turning the flywheel further until the Allen wrench could be replaced in the manner described earlier. This rotation of the flywheel from neutral position to neutral position subjected the specimen to one complete cycle. The recorded strain measurements enabled calculation of the tensile strain, compressive strain, total strain range, and the cyclic strain (zero-to-peak strain, or half the total strain range). Hand cycling of the specimen continued in order that strain measurements could continue to be made for the second and fifth through tenth cycles. Cyclic strains measured for cycles six through ten were averaged and recorded as the cyclic strain to which the gage was subjected for an individual test. In several of the tests, the specimen was hand-cycled up to 100 cycles enabling a strain measurement at this point. The S/N meter was reconnected at various cycles between one and ten to facilitate the taking

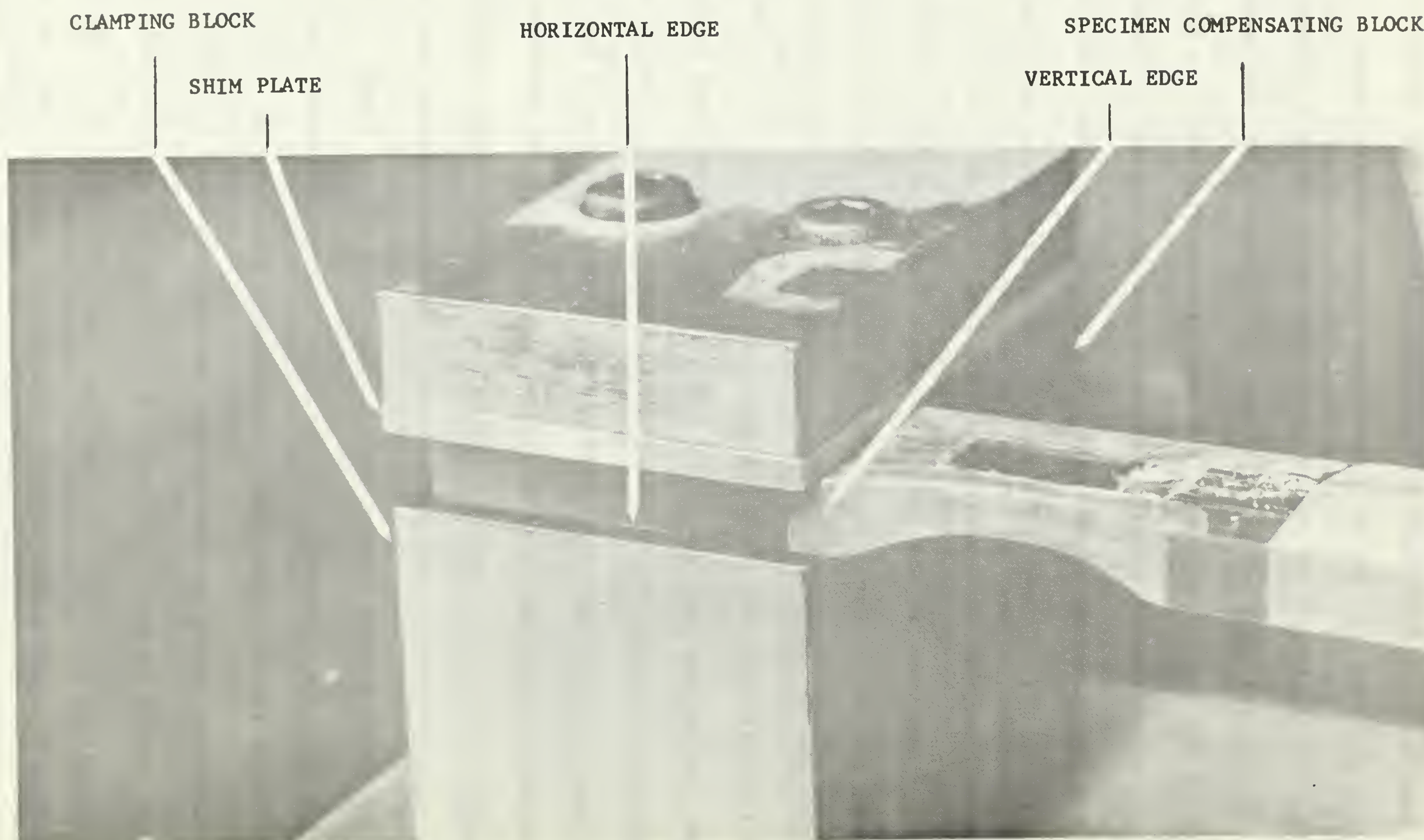

FIGURE 1. SPECIMEN MOUNTED IN CLAMPING BLOCK

of gage resistance readings. It was normally left connected to the gage after cycle number ten for the duration of the test excepting those few tests where strain measurements were made at 100 cycles. The specimen was returned to the neutral position for each gage resistance reading.

The averaged cyclic strain and the resistance of the gage recorded at ten cycles were used as the test cyclic strain and reference gage resistance value respectively. These values were used rather than the initial (zero cycle) values so as to minimize the effects of plastic flow and of "seating" of the specimen [Ref. 7].

With these initial strain measurements and the reference gage resistance recorded, the hand-cycling was terminated and the test continued using the variable speed electric motor. The motor was operated at a speed which subjected the specimen to a bending rate of 1800 CPM. A tachometer was used periodically during each test to assure this rate being maintained. Once started, the fatigue machine was run at this speed until the electronic counter indicated the number of elapsed cycles desired for the next gage resistance reading. Cyclic intervals between measurements varied with each individual test. With each successive resistance reading, the gage resistance change was calculated relative to the reference resistance. This change was plotted versus the elapsed number of cycles on log-log paper (See Appendix D). This plot offered a means of comparison between the behavior of the gage during a test and the behavior predicted by the manufacturer.

A most important portion of each test conducted was the determination of the gage resistance change at the inception of a crack in a specimen. During the first few tests conducted, Manson's predicted fatigue life for 70-30 copper-nickel (Appendix C) proved useful in determining when to commence inspection of the specimen for cracks. It offered a means of

determining at what number of cycles, for a particular cyclic strain, to begin the examination. Initially, it was not known how good this prediction was; therefore, specimen examination was usually begun several thousand cycles before the predicted number of cycles to crack initiation. The prediction served its purpose in that it eliminated the need to examine the specimen throughout the entire test. After several tests were completed, it was apparent that the minimum resistance change registered by the gage at crack iniation was approximately 4.3 ohms. With this knowledge, inspection for cracks in subsequent test runs started when the resistance change reached 0.5 ohms below the anticipated 4.3 ohms as suggested in Ref. 11.

Inspection for cracks was conducted in the following manner:

1. to accentuate the cracks, a thin coating of W. T. Bean Solder Stop was applied to the specimen prior to cycling (Appendix A);

2. a flexible fluorescent desk-type lamp was positioned near the machine;

3. specimen was placed in tension by rotation of the flywheel by hand;

4. by maneuvering the fluorescent lamp to provide different lighting angles, the specimen surface was examined with an 8X eyepiece (similar to a jeweler's eyepiece).

Inspection of the specimen surface for cracks is a procedure which has to be conducted meticulously and without regard to time. A crack which might appear under one particular light angle often did not appear under another angle. By maneuvering the lamp to different positions and carefully examining the specimen surface under each lamp position, chances of crack detection are improved. Figures 2 through 9 inclusive, illustrate some of the cracks actually detected on individual specimens.

In taking these photographs through the metallograph, the Solder Stop coating was left intact in an attempt to illustrate how this coating accentuates the cracks. With a crack detected, the resistance change at that number of cycles was recorded and the test terminated.

As suggested in Ref. 11, several tests were run at each of two convenient strain amplitudes. By performing several tests at a particular strain amplitude, it was possible to obtain the average number of cycles required to generate cracks as well as the average resistance change in the gage.

FIGURE 2. ARROW ON CAM IN NEUTRAL POSITION

FIGURE 3. FIRST CRACK, SPECIMEN #4, 150X

FIGURE 4. FIRST CRACK, SPECIMEN #6, 150X

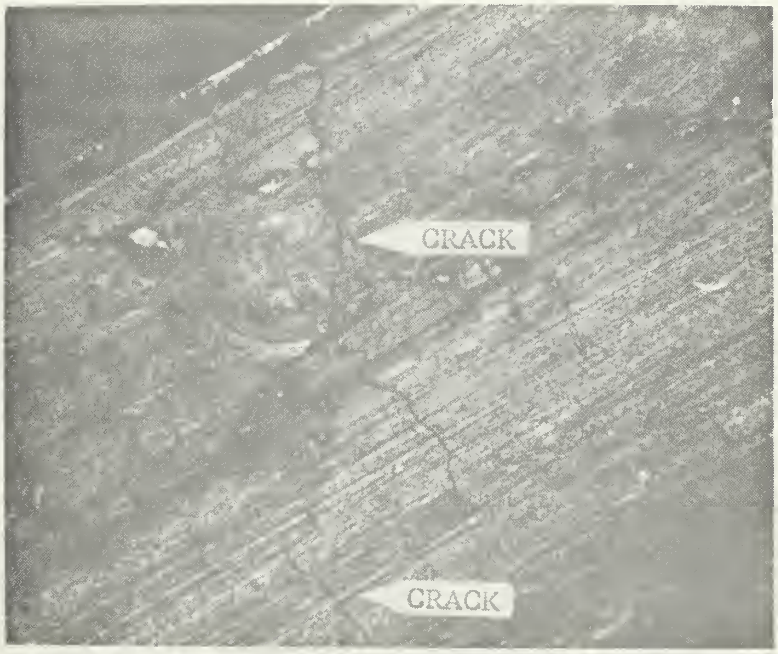

FIGURE 5. FIRST CRACK, SPECIMEN #8, 100X

FIGURE 6. FIRST CRACK, SPECIMEN #7, 150X

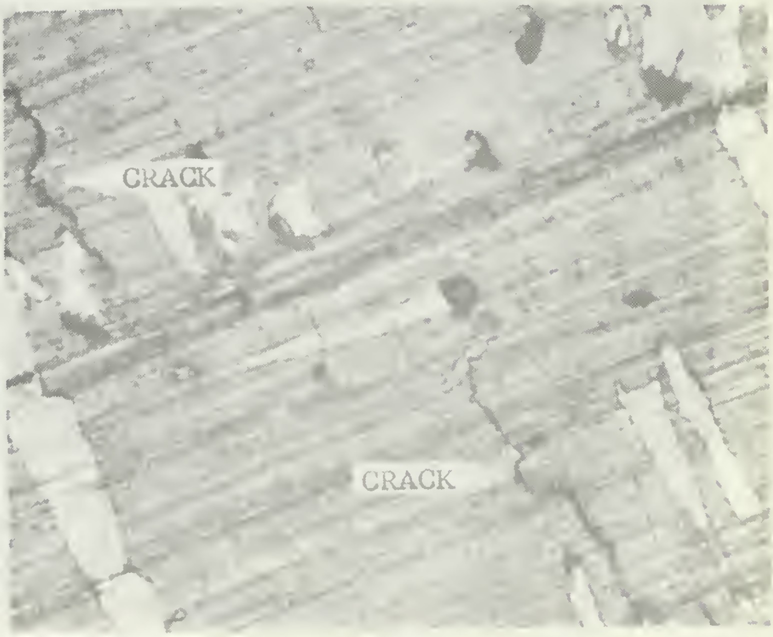

FIGURE 7. SECONDARY CRACKS, SPECIMEN #7, 150X

FIGURE 8. CRACKS NOTED IN SPECIMEN #9, 200X

FIGURE 9. CRACKS NOTED IN SPECIMEN #9, 200X

III. PRESENTATION OF TEST RESULTS

TABLE 1

SUMMARY OF TEST RESULTS

Test No.	Clamping Block Pos.	Distance δ	Distance α	Cyclic Strain ϵ_R	Resistance Change ΔR	Cycles N_o	Note* No.
1	1	.469	.113	2457	4.22	20010	1,2,3
2	1	.469	.113	2135	4.76	21010	1,2
3	1	.469	.113	2682	4.56	18000	2
4	1	.469	.129	2380	4.33	23050	2
5	1	.484	.113	2701	4.58	20012	4
6	2	.453	.113	4041	4.98	5015	5
7	1	.484	.113	2744	4.50	17005	6
8	1	.484	.113	2833	4.55	18000	7
9	2	.484	.113	4317	4.61	3286	
10	2	.531	.05	3706	4.56	4694	8
11	2	.516	.05	4256	4.70	3207	9
12	2	.516	.05	4167	4.77	3510	
13	2	.516	.05	4253	4.68	3000	
14	2	.531	.05	4078	4.59	3171	

*Notes begin at bottom of page 27.

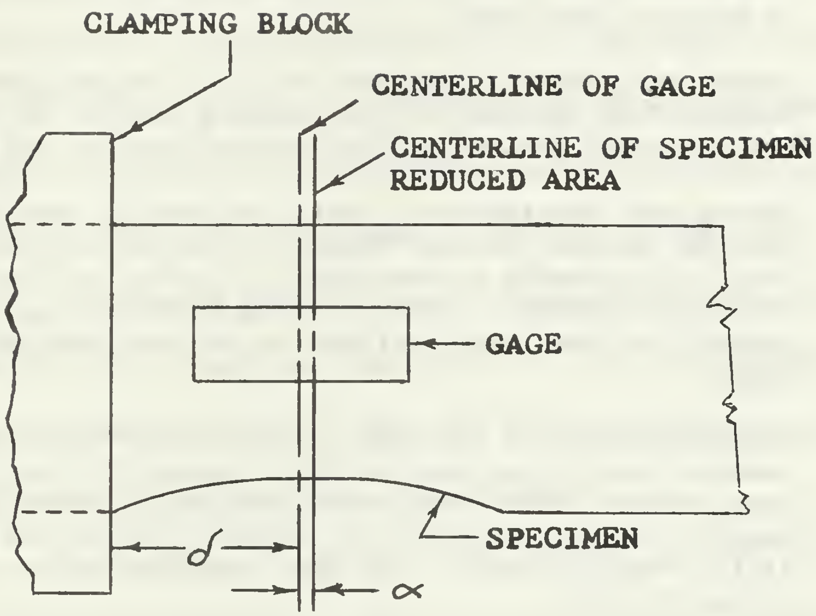

FIGURE 10. SCHEMATIC OF GAGE, SPECIMEN, AND CLAMPING BLOCK CONFIGURATION

TABLE 2

MEAN VALUES FOR DIFFERENT STRAIN LEVELS

Clamping Block Position	Average Cyclic Strain	Average ΔR	Average N_o	Note No.
1	2740	4.55 (+.03,-.05)	18224	10
2	4214	4.67 (+.10,-.08)	3235	11

Notes:

1. The cyclic strains recorded for each of these two tests indicate approximate values. They should not be interpreted as average cyclic strain levels for the test as only initial strain measurements were made over the first ten cycles so as to arrive at an average cyclic strain level.

2. For these four tests, a reference resistance value for the gage was not established in the manner suggested by reference 8. Familiarization with the equipment and with crack detection techniques was attained during these tests.

3. Specimens for tests one through ten were made up in a single batch. Even so, it was noted that the lengths as well as the thicknesses of their individual reduced areas varied by as much as .002 inch.

4. During this test, a standard procedure was developed for mounting the specimen in the clamping block. This procedure was carefully adhered to for the remainder of the tests.

5. Microscopic examination of this specimen at completion of testing revealed several cracks in the general vicinity of that crack thought to have been the first to occur. Some of these appeared to be more advanced which suggested the possibility that crack initiation occurred earlier than noted.

6. Upon completion of the gage installation, visual examination revealed some discoloration which appeared to be under the gage surface. This raised the question of a poor bond; however, the portable strain indicator offered no evidence of drift from null value. The gage exhibited normal behavior during the test.

7. In this test, the gage was placed so that its transverse axis did not coincide with the transverse layout line burnished on the specimen surface, (Appendix A), but was slightly canted.

8. Commencing with this test, the gage centerline was positioned .05 inch (distance $\propto$, Figure 10), from the centerline of the reduced section of the specimen as recommended by Ref. 8.

9. The specimens for this and the remaining tests constitute another batch, all of which were carefully machined by one machinist. No dimensional discrepancies were noted in these specimens.

10. These values were obtained by averaging the data from tests three, five, seven, and eight, as suggested by Refs. 8 and 9. In these tests, all gages were subjected to approximately the same cyclic strain.

11. The average values recorded for clamping block position two were obtained from the data for cycles 9, 11, 12, 13 and 14. In these tests, all gages were subjected to approximately the same cyclic strain. Data from test number six was not included because, as implied in note five, there is a question as to its validity.

IV. CONCLUSIONS

The conclusions reached in this investigation are as follows:

1. The performance of an S/N gage when bonded to 70-30 copper-nickel and subjected to cyclic strain shows the same smooth relation between number of strain cycles and cumulative change in gage resistance, up to the point of failure of the specimen, as has been observed by the manufacturer and others when this gage is applied to other materials.

2. The average gage resistance changes at crack initiation for the two clamping block positions considered in this investigation were 4.55 (+.03,-.05) ohms and 4.67 (+.10,-.08) ohms at (average) cyclic strain of 2740 and 4214 microstrain, respectively.

3. The values of gage resistance change at crack initiation recorded in this investigation support the conviction that with further laboratory study practical proposals for use of the S/N Fatigue Life Gage to monitor in-service cumulative damage of 70-30 copper-nickel may be developed.

V. RECOMMENDATIONS

In order to permit additional evaluation of the possibilities of in-service application of the S/N Fatigue Life Gage as a monitor of cumulative fatigue damage in 70-30 copper-nickel, continued laboratory investigation is recommended.

The following tests and procedures are recommended for inclusion in such an investigation:

1. Several tests should be conducted at other constant strain amplitudes such as: 1000, 1500, 2000, 3000, and 3500 micro-strain. An average change of gage resistance at specimen crack initiation should be determined for each of the strain amplitudes.

2. A number of tests in which the gage is exposed to more than one strain amplitude (i.e., block-cycling) should be performed. Several combinations of strain amplitudes ought to be used.

3. As the above tests can each be completed in a matter of hours, "aging" effects on gages mounted on 70-30 copper-nickel are not known. To determine what effects, if any, aging might have on the S/N gages could be achieved by preparing some specimens, loading them for several hundred cycles, resting them for periods of various intervals (hours or days), and loading them again for several hundred more cycles. The resistance changes recorded for these tests should be compared with those measured in the previous tests.

As manufactured, the S/N Fatigue Machine limits an investigator to two clamping block positions (i.e., two strain levels) for a block-cycling test. With the specimen designed as suggested in Ref. 11, the third clamping block position (i.e., third strain level) cannot be used

without shortening the design length of the specimen to avoid interference with the electric motor. The three clamping block positions that are provided restrict the user to three strain amplitudes. To obtain other amplitudes, the longer end of the specimen must be remachined to reduce its thickness below the designed .25 inch.

It is recommended that consideration be given to re-design of the present machine to relieve restrictions such as the above. The following are some recommended modifications for the present machine:

1. Position of the motor on the base plate: Repositioning of the variable speed electric motor would eliminate the problem of shortening the specimen to use clamping block position three. To accomplish this, the machine base plate might be widened to permit the motor to be removed from its present position on one side of the machine flywheel to a new position on the other side of the flywheel (i.e., turned 180° about a vertical axis).

2. Provisions for additional clamping block positions: Such provisions would increase the number of strain levels immediately available to an investigator. The need to remachine a specimen would be eliminated. At present, the clamping block is secured in a position on the base plate by two bolts passing through positioning holes provided in the base plate. There are four such holes existing in the present base plate. By lengthening the base plate and drilling more positioning holes, several more clamping block positions would be readily available. With these additional positions, an investigator could block cycle a specimen using several strain amplitudes without having to disturb positioning of the specimen within the clamping block. It is realized that the length of the specimen would have to be increased, but this should

not create a problem if other design dimensions of the specimen are not altered.

3. Specimen positioning in the clamping block: During each test, considerable time was expended in positioning the specimen within the clamping block as described in Section II. Consideration should be given the design of a jig or some other means for efficiently positioning the specimen in the clamping block in a like manner for each test.

APPENDIX A

PREPARATION OF REVERSED BENDING TEST SPECIMENS

All specimens were fabricated from 70-30 copper-nickel. The specimen geometry was patterned after the W. T. Bean S/N plain fatigue specimen as shown in Figure 11. This geometry was chosen for the following reasons:

1. The specimen was designed for use with the W. T. Bean S/N Fatigue Machine;

2. Manufacturer's predicted gage performance curves have been based upon this specimen geometry.

The test specimens were cut from a .325 in. x 12 in. x 24 in. 70-30 copper-nickel plate (Figure 11). They were machined by a shaper to overall length and width, followed by milling with a slow feed to produce the finished surface and reduced section. This material was difficult to machine,making the entire process tedious. It not only tended to warp, making it hard to hold in a flat position, but it dulled tools rapidly. It was necessary to check the sharpness of the tools frequently.

The procedure followed in the surface preparation of the specimens is as follows:

1. Clean specimen surface with gauze saturated with Chlorothene NU Degreaser;

2. Wet lap all sides of the reduced section of the specimen with 320 grit silicon carbide paper and metal conditioner (Conditioner A), and wipe dry with a clean tissue; (for uniformity, all sides of the reduced section were finished in this manner until microscopic examination

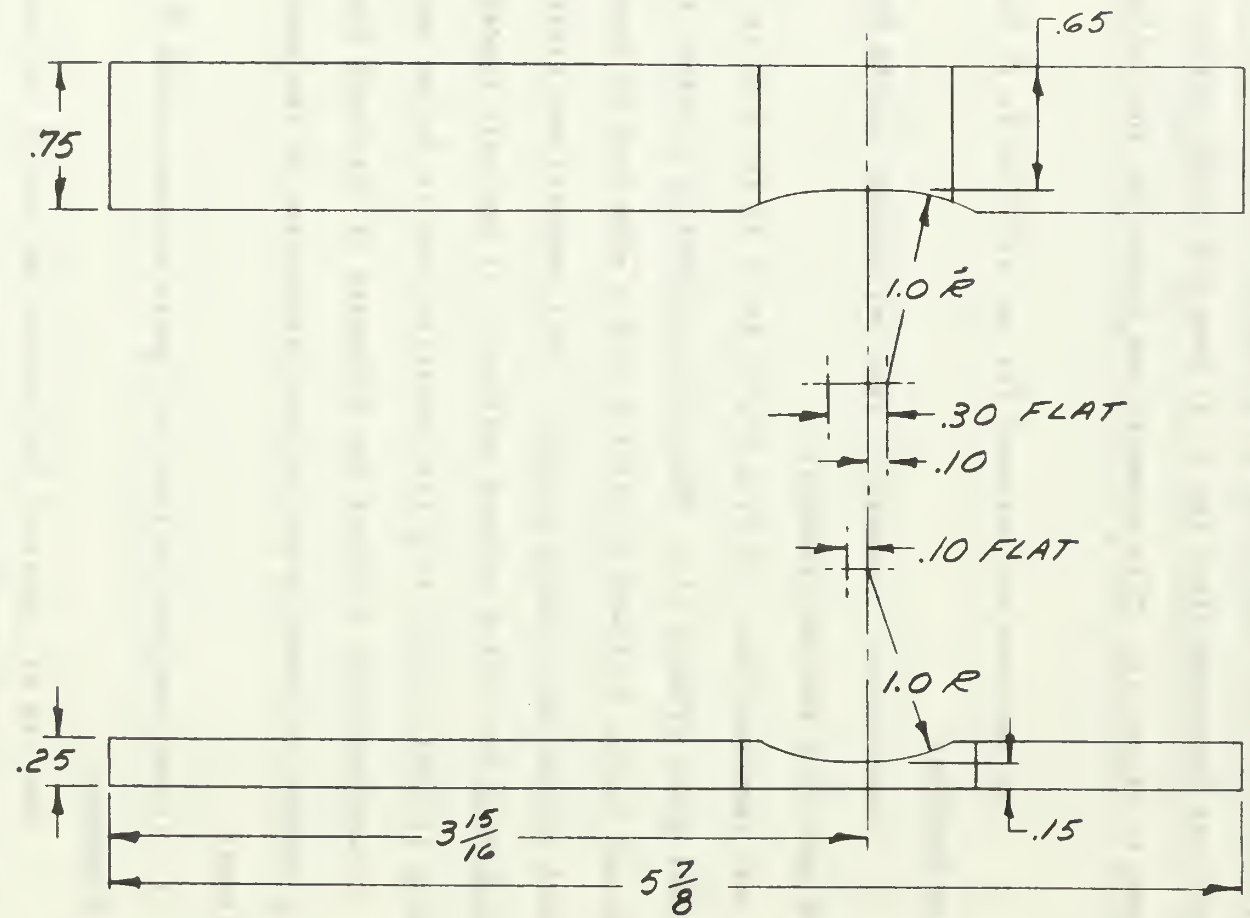

FIGURE 11. TEST SPECIMEN DESIGNED BY W. T. BEAN
(Reproduced by permission)

at 30X confirmed the removal of any gross machining marks).

3. Wet lap the flat portion of the reduced section where the S/N Fatigue Gage is to be located with 400 grit silicon carbide paper and metal conditioner (Conditioner A) and wipe dry with a clean tissue;

4. Repeat step 3 and indicate gage position with a 4-H pencil; (normally, the centerline of the gage should be positioned 1/16 inch toward the clamped end of the specimen from the centerline of the reduced section, however, in the tests reported in this paper, this dimension did vary. See notes on the individual tests in Section III);

5. Apply metal conditioner (Conditioner A) to the surface with a cotton swab and remove with one firm stroke of clean tissue;

6. Wash hands with neutralizer;

7. Apply Isopropyl Alcohol to the surface with a cotton swab and remove with one firm stroke of clean tissue;

8. If specimen is allowed to stand for more than twenty minutes before the gage application, it is advisable to repeat step 7.

With the specimen surface prepared in the above manner, an S/N Fatigue Gage was mounted on the flat surface of each specimen.

The following gage installation procedure was used for each specimen:

1. Place the bonding side of the gage on a smooth, clean surface (such as glass, teflon, or paper) along with some fine pumice powder and lap with a circular motion of the forefinger, applying a light uniform pressure while doing so;

2. Place the gage face-up (i.e., bonding side down) and place an acetate envelope over the leads (this is applicable to type FWA-01 gages with integral leads, such as were used in this investigation); (See Figure 13);

3. Trim a piece of adhesive cellophane tape so that the width is approximately 1/2 the length of the gage backing;

4. Attach the tape to the lead end of the gage and carefully fold the leads up from the surface 60 degrees with the acetate envelope (see drawings in Ref 7);

5. Remove the acetate envelope, being careful not to damage the leads;

6. Carefully lift the gage assembly from the working surface and clean the bonding surface of the gage with a cotton applicator slightly moistened with Isopropyl Alcohol;

7. Place the gage in position on the specimen over the lay-out lines; (in all tests conducted, the gage was positioned with its lead-end away from the clamped end of the specimen towards the lower strain field);

8. Starting at one end of the cellophane tape, lift the gage leaving the other end of the tape attached to the specimen;

9. Mask around the gage area with masking tape to prevent excessive flow of Eastman 910 adhesive over the surface of the specimen;

10. Apply a thin film of blue 910 catalyst to the back of the gage and allow to dry for approximately one minute;

11. Apply two drops of Eastman 910 adhesive to the gage area of the specimen;

12. Lift the end of the cellophane tape and gage over the adhesive at an angle of 45 degrees;

13. With a piece of teflon film make a single firm stroke over the tape (similar to hanging wallpaper);

14. Within one second, press the gage firmly into contact with

the surface using a thumb or finger and maintain pressure for approximately thirty seconds;

15. Wait at least two minutes before removing the cellophane tape from the top of the gage by pulling it back over the gage with the tape remaining parallel to the surface. After the gage is installed, a terminal strip is mounted adjacent to the lead-end of the gage using the same installation procedure outlined above. In this position the terminal strip is in a lower strain field and the gage leads are led away from the high strain field.

A three-wire hookup as shown below should be used for the lead-wire system.

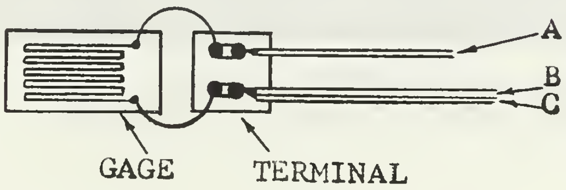

FIGURE 12. THREE-WIRE LEADS TO GAGE

In wiring the gage leads and the lead wires to the terminal strip, the procedure used is as follows:

1. Cover the installed S/N Fatigue Gage with a piece of masking tape to protect it against solder spatter;

2. Tin the terminal strip with fresh solder;

3. Strip the lead-in cable back approximately 1/2 inch;

4. Separate the strands of A (from the strands of B and C) and twist together;

5. Twist the strands of B and C together;

6. Tin the twisted strands and cut the leads off to approximately 1/8 inch from the insulation;

7. Spring load the leads against the terminal strips with masking tape and apply fresh solder;

8. Form the integral gage leads to a uniform C-shape, spring load against the terminal strip and apply fresh solder;

9. Remove the masking tape and solder flux by flushing the entire installation with rosin solvent, (M-Line Rosin Solvent)*;

10. Using masking tape, mask off the gage installation area and waterproof the completed installation with a thin coat of M-Line, M-Coat A (polyurethane)*, (See Figure 14 for an overhead view of a completed gage installation).

To complete the preparation of the specimen, a thin coat of Solder Stop was applied to the area surrounding the gage installation. Solder Stop, a W. T. Bean product, proved very effective in permitting early detection of cracks.

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*Products of Micro-Measurements, Inc., Romulus, Michigan, recommended for use in applying S/N gages.

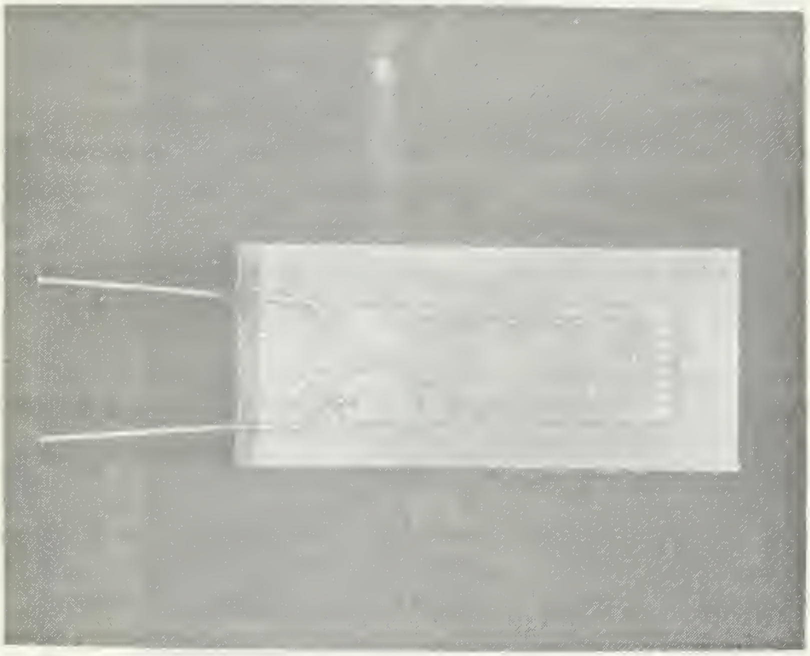

FIGURE 13. FWA-01 GAGE AS RECEIVED FROM THE MANUFACTURER PRIOR TO INSTALLATION

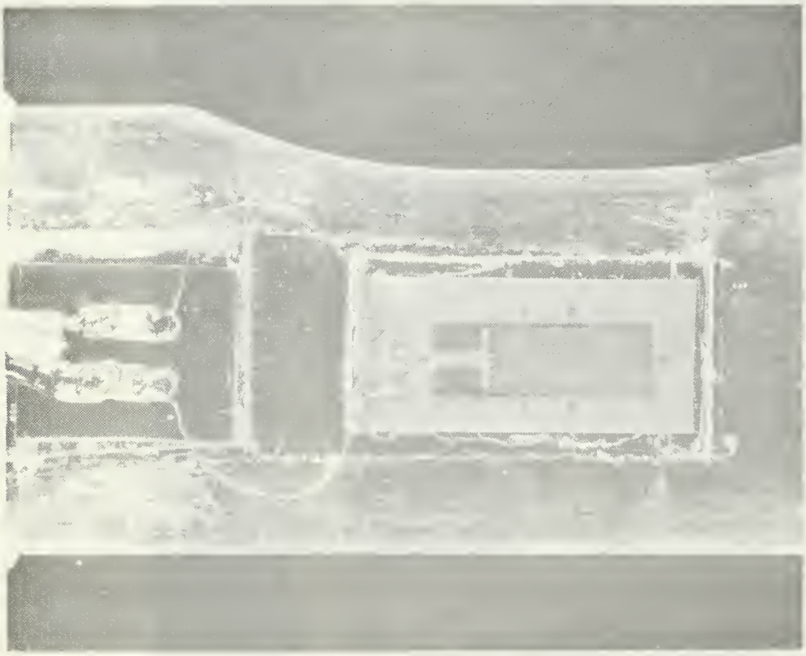

FIGURE 14. COMPLETED GAGE INSTALLATION

APPENDIX B

DESCRIPTION OF APPARATUS

S/N FATIGUE MACHINE

To evaluate the performance of the S/N Fatigue Gage on 70-30 copper-nickel, a W. T. Bean S/N Fatigue Machine was used. This type of apparatus has been used in determining the manufacturer's predicted gage characteristics.

The machine is a constant displacement device for low-cycle fatigue studies. Several levels of operating strain magnitudes are provided. The strain level is determined primarily by varying the position of the specimen clamping block or by varying the specimen thickness.

The manufacturer has painted a diametrical stripe on the machine flywheel so that a strobe light may be used for counting cycles. To obtain a more accurate cycle count, an optical tachometer pickup was used in conjunction with an electronic counter, see Figure 15. Information applicable to the components of the counting circuit is as follows:

Tachometer Head

Manufacturer: Hewlett-Packard
Model: 506A
Serial Number: 003-01394

Regulated D. C. Power Supply

Manufacturer: Power Designs, Inc.
Model: 3650-S
Serial Number: 703001
Volts: 36
Amperes: 5

Electronic Counter

Manufacturer: Hewlett-Packard
Model: 522B
Serial Number: 2453

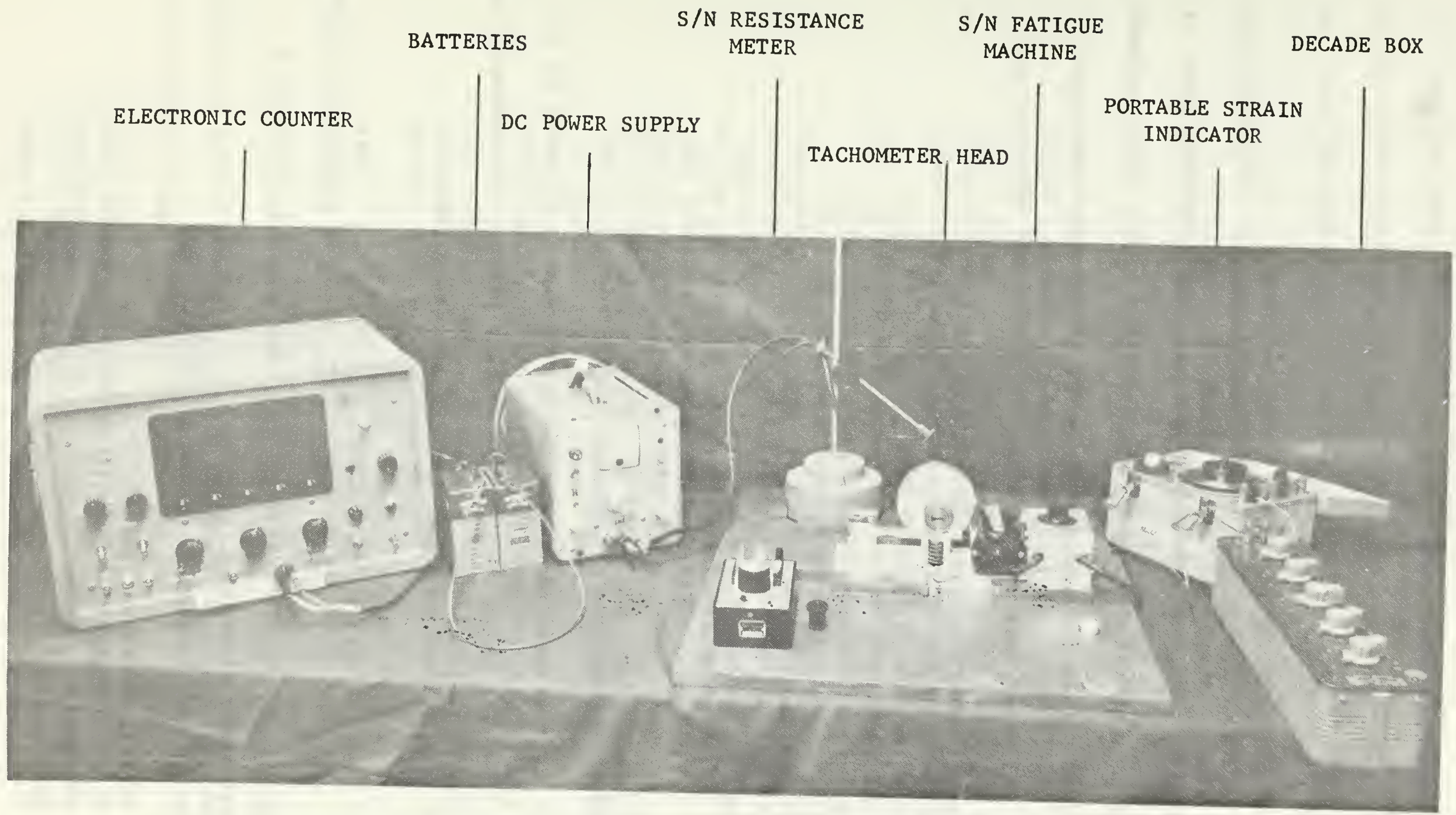

FIGURE 15. EQUIPMENT SET-UP FOR TEST

Batteries

Manufacturer: Eveready
Quantity: two
Type: B
Number: 762-5
Volts: 45

S/N FATIGUE LIFE GAGES

S/N Fatigue Life Gages consist of a constantan foil grid which is encapsulated in a glass-fiber/epoxy laminate [Ref. 10]. They are provided in various sizes and with either solder terminals or integral leads. The following information is applicable to the S/N gage used:

Manufacturer: Micro-Measurements, Inc.
Gage type: FWA-01 (with integral leads)
Gage resistance: 100.00 ohms $\pm$ 0.2%
Gage factor: 2.04
Gage length: 0.25 inches
Overall pattern length: 0.375 inches
Grid width: 0.125 inches
Overall pattern width: 0.125 inches
Backing matrix
  length: 0.55 inches
  width: 0.18 inches

70-30 COPPER-NICKEL SHEET

All of the test specimens were fabricated from a 12 in. x 24 in. piece of 0.3125 inch thick 70-30 copper-nickel plate. The chemical composition of this particular plate section was as follows:

Cu %	Ni %	Zn %	Pb %	Fe %	Mn %	P %	S %	TOE* %
69.1	29.8	0.08	0.01	0.59	0.43	.008	.005	0.50

*TOE = total other elements

The mechanical properties of the plate were:

Tensile strength: 53 ksi
Yield strength: 22 ksi
Elongation: 49.5%
Hardness: 47 R_B

Reduction in area: 88.3%
Young's Modulus of elasticity: 24.6×10^6 psi

The chemical composition and mechanical properties were provided by Mr. H. G. MacKerrow, Head, Metallurgical Laboratory Branch, San Francisco Bay Naval Shipyard, Vallejo, California.

BUDD/STRAINSERT PORTABLE STRAIN INDICATOR

The portable strain indicator was used to obtain all strain readings. The following information and specifications are applicable:

Manufacturer: Strainsert Company
Model: HW-1
Serial Number: 0431
Total range: 60,000 micro-strain ($\pm$ 30,000 micro-strain)
Range of measure dial: 10,000 micro-strain
Number of intervals: six as follows (in micro-strain)
0-10,000
10,000-20,000
20,000-30,000
both in tension (+) and compression (-)
Accuracy: 0.1% of reading or 5 micro-strain
Readibility: 1 micro-strain
Types of circuits: 1, 2, or 4 arm bridge
Bridge Circuit selection: with shorting links
Gage factor adjustment: 1.50 to 4.50
Gage resistance: 50 to 2000 ohms
Bridge excitation: 1½ volts, 500 cps, square wave
Lead wire capacitance adjustment: not required to 500 feet of twisted wire
Battery: One (1) nine (9) volt battery
Oscilloscope jack: 3 millivolts maximum signal for 3000 micro-strain, at G.F.= 2.00
Case construction: Aluminum - dust and spray tight
Size: 9 in. x 6 in. x 6 in.
Weight: 6.5 lbs.

DECADE RESISTANCE BOX

A decade resistance box was used in the half bridge circuit while making all strain readings. Information applicable to the decade box used is as follows:

Manufacturer: General Radio Co.
Type Number: 1432-M
Serial Number: 22141
Range: 0-11,000 ohms

S/N RESISTANCE METER

The S/N Resistance Meter was used to measure all resistance changes. (Figure 15) It is a null-balance, Wheatstone bridge type of instrument designed to measure increments of resistance change in S/N Fatigue Life Gages. It possesses a five digit dial which reads ohms resistance in 10's, 1's and 0.1's above the base value. A three wire input to the meter compensates for lead wire resistance.

Since the manufacturer did not provide data pertaining to the accuracy of the instrument, a calibration run was made using the aforementioned General Radio Decade Resistance Box. The meter accurately indicated each resistance set on the decade box. Results of this calibration test as well as information applicable to the S/N Resistance Meter are as follows:

TABLE 3

CALIBRATION TEST OF S/N RESISTANCE METER

Decade Resistance Box Resistance (ohms)	S/N Resistance Meter Reading (ohms)
99	99
100	100
101	101
102	102
103	103
104	104.01
105	105.01
106	106.02
107	107
108	108
109	109.02
110	110
120	120
130	130
140	140
145	145
150	150
160	160
170	170
180	179.98
190	189.97
195	194.98

S/N Resistance Meter, Serial No. 69084 Mfg. by Bach-Simpson Ltd., Canada.

METALLOGRAPH

All photographs of cracks were taken through a Bausch and Lomb Dynazoom Bench Metallograph (Catalog Number 42-31-52-31, Serial Number 1882) fitted with a 4 in. x 5 in. Polaroid camera.

APPENDIX C

MANSON'S EQUATION FOR PREDICTION OF FATIGUE LIFE

In the determination of resistance change at crack initiation, it was useful, initially, to have an indication of fatigue life for 70-30 copper-nickel. In Reference 6, S. S. Manson offers a method for predicting the fatigue life of structural materials subjected to constant amplitude cyclic strains. Manson's equation for life to fracture at a particular cyclic strain is:

$$\epsilon_R = 1.75 \times 10^6 \frac{\sigma_u}{E} N_f^{-0.12} + 5 \times 10^5 \left(\frac{D}{N_f}\right)^{0.6}$$

where

ϵ_R = cyclic strain ($\pm$ zero-to-peak microstrain)

σ_u : ultimate strength, psi

E : Young's Modulus of Elasticity, psi

N_f : number of applied cycles to complete fracture of the specimen

N_o : number of applied cycles to iniation of crack in specimen

D : $\ln \frac{1}{1-RA}$

RA : reduction in area per unit area

Using values for 70-30 copper-nickel given in Appendix B, the upper curve in Figure 16 was obtained from this formula. By dividing N_f by two as is suggested in Ref. 8, the approximate number of cycles to crack iniation, N_o, was obtained and plotted. This is the lower curve in Figure 16.

From this plot, it was possible to estimate the number of cycles at which specimen cracking should begin for a particular strain level.

Thus, the plot offered an initial guide in determining when to start inspection for cracks.

As a point of interest, the crack initiation data obtained in the present investigation is also shown. It is seen that the Manson curve, modified for crack initiation rather than complete failure, is consistent with the data obtained in this investigation.

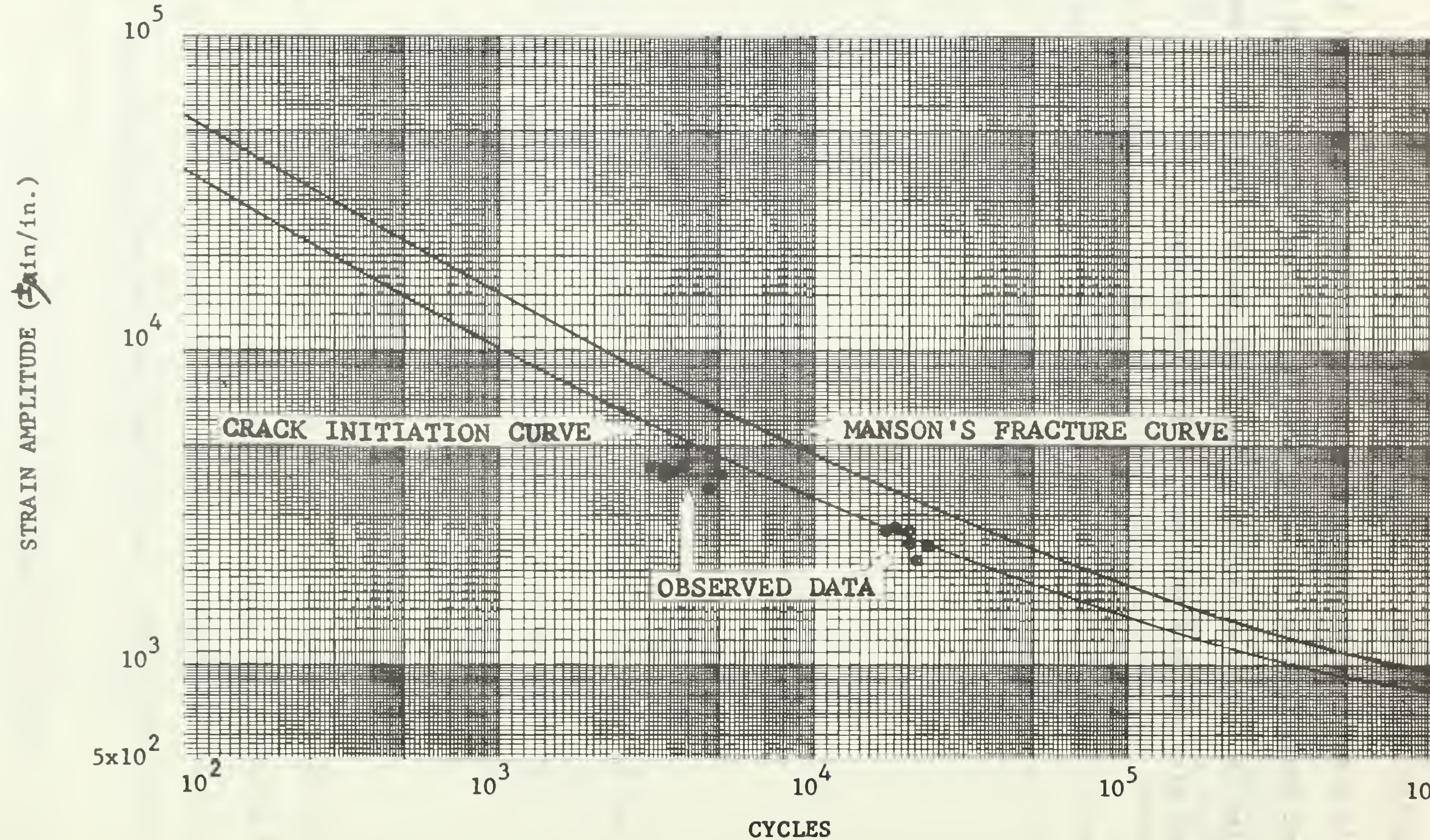

FIGURE 14. MANSON'S PREDICTED LIFE CURVE FOR 70-30 COPPER-NICKEL

APPENDIX D

TABULATION OF DATA

Raw data, transcribed from laboratory data sheets, appears on the next 14 pages. This material is included so as to permit the reader to perform whatever manipulations of the data he might find of interest.

Test #1

Clamping block position: 1

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
1	100.46	0.0	*	1409	3505	4914	2457
950	101.30	0.84					
1511	101.76	1.30					
2505	102.15	1.69					
3995	102.82	2.36					
6015	103.34	2.88					
8007	103.70	3.24					
10000	103.96	3.50					
15000	104.41	3.95					
18011	104.65	4.19					
20010	104.78	4.22					

*Null reading was not recorded for this test.

Test #2

Clamping block position: 1

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
1	100.0	0.0	*	2018	2076	4094	2047
4				2028	2242	4270	2135
100	100.13	0.13					
492	100.62	0.62					
1008	101.05	1.05					
2475	101.98	1.98					
6000	103.17	3.17					
8000	103.50	3.50					
10010	103.80	3.80					
15016	104.33	4.33					
18000	104.52	4.52					
20010	104.62	4.62					
21010	104.76	4.76					

*Null reading was not recorded for this test

Test #3

Clamping block position: 1
Strain level: $\pm 2682 \mu\epsilon$
α : .113"
γ : .469"

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
1	100.12	0.0	113	2073	3340	5413	2706
5			237	2092	3523	5615	2807
6			197	2017	3358	5375	2687
7			200	2008	3360	5368	2684
8			239	2024	3333	5357	2678
9			231	2003	3349	5352	2676
10			240	2010	3360	5370	2685
1000	100.80	0.68	5350	2040	3520	5560	2780
2500	102.13	2.01					
6000	103.20	3.08					
8000	103.60	3.48					
10000	103.85	3.73					
12500	104.12	4.00					
15000	104.32	4.20					
17005	104.48	4.36					
18000	104.68	4.56					

Test #4

Clamping block position: 1
Strain level: $\pm 2380\mu\epsilon$
α : .129"
δ : .469"

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
1	100.1	0.0	312	2505	2230	4735	2368
5			135	2275	2485	4760	2380
6			173	2310	2444	4754	2377
7			223	2379	2424	4758	2379
8			028	2128	2633	4761	2380
9			205	2298	2465	4763	2381
10	100.11	0.01	138	2221	2544	4765	2382
100	100.23	0.13	170	1950	3000	4950	2475
510	100.63	0.53					
1000			160	2050	3290	5340	2510
1100	101.14	0.94					
2100	101.55	1.45					
3000	101.93	1.83					
5000	102.52	2.42					
7000	102.93	2.83					
9000	103.24	3.14					
10000	103.40	3.30					
12600	103.66	3.56					
13600	103.80	3.70					
15100	103.91	3.81					
17100	104.06	3.96					
18000	104.15	4.05					
19000	104.22	4.12					
20000	104.28	4.18					
21000	104.32	4.22					
22000	104.35	4.25					
23050	104.43	4.33					

Test #5

Clamping block position: 1
Strain level: $\pm 2701 \mu\epsilon$
α : .113"
δ : .484"

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
0	100.24	0.0	988	2401	2946	5347	2673
1	100.19		646	2050	3325	5375	2688
5	100.22		851	2204	3191	5395	2698
6			727	2064	3331	5395	2698
7			760	2068	3334	5402	2701
8			781	2073	3328	5401	2700
9			789	2069	3339	5408	2704
10	100.22	0.0	799	2068	3348	5406	2703
100	100.37	0.15	1558	2131	3421	5552	2776
200	100.50	0.28	2224	2153	3480	5633	2816
500	100.83	0.61					
1002	101.21	0.99					
3010	102.32	2.10					
7012	103.45	3.23					
10014	103.91	3.69					
14014	104.37	4.15					
15008	104.44	4.22					
16515	104.54	4.32					
17000	104.60	4.38					
18012	104.68	4.46					
19006	104.74	4.52					
20012	104.80	4.58					

Test #6

Clamping block position: 2
Strain level: $\pm 4014 \mu\epsilon$
α : .113"
δ : .453"

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
0	100.25		997	3709	4493	8202	4101
1	100.10		228	2887	5264	8151	4025
5	100.14		521	2986	5084	8070	4035
6			463	2883	5169	8052	4026
7			588	2906	5124	8030	4015
8			578	2847	5170	8017	4009
9			655	2889	5123	8012	4006
10	100.18	0.0	740	2946	5076	8025	4013
100	100.62	0.44	2770	2969	5185	8154	4077
200			4570	3001	5201	8201	4100
493	101.76	1.58					
1543	103.28	3.10					
1993	103.76	3.58					
2509	104.13	3.95					
2991	104.44	4.26					
3334	104.61	4.43					
3498	104.66	4.48					
3796	104.78	4.60					
3996	104.87	4.69					
4569	105.04	4.86					
4696	105.08	4.90					
4797	105.10	4.92					
4895	105.14	4.96					
5015	105.16	4.98					

Test #7

Clamping block position: 1
Strain level: $\pm 2744 \mu\epsilon$
α : .113"
δ : .484"

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
0	100.07		-36	2162	3278	5440	2720
1	100.04		-87	2120	3335	5455	2728
5	100.05		5	2158	3325	5483	2741
6			-43	2109	3373	5482	2741
7			-30	2100	3382	5482	2741
8			- 8	2106	3379	5485	2742
9			3	2115	3387	5502	2751
10	100.05	0.0	6	2098	3398	5496	2748
100	100.21	0.16	847	2172	3461	5633	2817
200	100.36	0.31	1558	2166	3533	5699	2850
997	101.17	1.12					
3003	102.30	2.25					
6012	103.18	3.13					
9008	103.73	3.68					
12006	104.12	4.07					
14008	104.24	4.19					
15008	104.40	4.35					
16012	104.51	4.46					
17005	104.55	4.50					

Test #8

Clamping block position: 1
Strain level: $\pm 2833 \mu\epsilon$
α : .113"
γ : .484"

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
0	100.12		318	2167	3542	5709	2855
1	100.12		302	2130	3576	5706	2853
5	100.13		416	2175	3496	5671	2835
6			351	2101	3581	5682	2841
7			397	2120	3545	5665	2832
8			420	2130	3530	5660	2830
9			420	2109	3553	5662	2831
10	100.13	0.0	424	2111	3551	5662	2831
100	100.32	0.19	1287	2187	3562	5749	2875
502	100.78	0.65					
1000	101.26	1.13					
4004	102.77	2.64					
7005	103.51	3.38					
10013	103.97	3.84					
12002	104.17	4.04					
14010	104.38	4.25					
15005	104.50	4.37					
16004	104.55	4.42					
16998	104.64	4.51					
18000	104.68	4.55					

Test #9

Clamping block position: 2
Strain level: $\pm 4317 \mu\epsilon$
α : .113"
δ : .484"

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
0	99.82		630	4902	4222	9124	4562
1	99.82		-1097	3073	5888	8961	4480
5	99.95		-585	3256	5473	8729	4365
6			-623	3140	5511	8651	4326
7			-722	3008	5649	8657	4328
8			-620	3070	5579	8649	4325
9			-578	3064	5548	8612	4306
10	99.97	0.0	-568	3021	5580	8601	4300
100	100.40	0.43	1637	3144	5524	8668	4334
221	100.82	0.85					
490	101.62	1.65					
1006	102.66	2.69					
1510	103.31	3.34					
2002	103.78	3.81					
2508	104.13	4.16					
2810	104.34	4.37					
2932	104.43	4.46					
3286	104.58	4.61*					
3539	104.69	4.72					
3713	104.78	4.81					
3908	104.86	4.89**					

*At this point, a crack was thought to be noticed
**At this point, the crack was verified

Test #10

Clamping block position: 2
Strain level: $\pm 3706 \mu\epsilon$
α : .05"
δ : .531"

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
0			655	3057	4365	7422	3711
1	100.11		360	2715	4706	7421	3711
5	100.17		711	2921	4489	7410	3705
6			527	2717	4695	7412	3706
7			558	2708	4693	7401	3701
8			609	2734	4680	7414	3707
9			617	2715	4694	7409	3705
10	100.18	0.0	637	2708	4714	7422	3711
100	100.54	0.36	2360	2796	4794	7590	3795
900	102.20	2.02					
1396	102.84	2.66					
1708	103.16	2.98					
2009	103.40	3.22					
2518	103.77	3.59					
3002	104.03	3.85					
3296	104.20	4.02					
3499	104.31	4.13					
3802	104.46	4.28					
4000	104.53	4.35					
4199	104.58	4.40					
4418	104.66	4.48					
4575	104.70	4.52					
4694	104.74	4.56					

Test #11

Clamping block position: 2
Strain level: $\pm 4256 \mu\epsilon$
α : .05"
δ : .516"

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
0	100.10		299	2961	5485	8446	4223
1	100.12		389	2961	5638	8599	4299
5	100.20		758	3065	5465	8530	4265
6			746	2998	5496	8494	4247
7			851	3074	5451	8525	4262
8			810	2999	5528	8527	4263
9			858	2976	5535	8511	4256
10	100.24	0.0	928	3028	5477	8505	4252
100	100.68	0.44					
508	102.02	1.78					
992	103.00	2.76					
1499	103.68	3.44					
2000	104.18	3.94					
2508	104.55	4.31					
2807	104.76	4.52					
2898	104.82	4.58					
3000	104.88	4.64					
3117	104.91	4.67					
3207	104.94	4.70*					
3300	105.00	4.76					
3400	105.02	4.78**					

*At this point, a crack was thought to be noticed
**At this point, the crack was verified. (Examination under 100X)

Test #12

Clamping block position: 2
Strain level: $\pm 4167 \mu\epsilon$
α : .05"
δ : .516"

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
0	100.22		885	3648	4715	8363	4181
1	100.13		260	3127	5416	8543	4271
5	100.20		553	3212	5150	8362	4181
6			371	2981	5370	8351	4176
7			411	2968	5366	8334	4167
8			488	2999	5326	8325	4163
9			479	2943	5381	8324	4162
10	100.23	0.0	539	2982	5353	8335	4167
104	100.63	0.40					
502	101.90	1.67					
1008	102.87	2.64					
1508	103.58	3.35					
2010	104.11	3.88					
2510	104.46	4.23					
2704	104.60	4.37					
2806	104.68	4.45					
2901	104.76	4.53					
3005	104.78	4.55					
3100	104.84	4.61					
3200	104.92	4.69					
3300	104.95	4.72					
3410	104.97	4.74					
3510	105.00	4.77					

Test #13

Clamping block position: 2
Strain level: $\pm 4253 \mu\epsilon$
α : .05"
δ : .516"

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
0	100.17		639	3738	4830	8568	4284
1	100.11		41	3044	5494	8548	4274
5	100.20		520	3322	5227	8549	4275
6			269	3006	5502	8508	4254
7			348	3014	5510	8524	4262
8			459	3062	5419	8481	4240
9			512	3099	5419	8518	4259
10	100.20	0.0	472	3014	5485	8499	4250
105	100.61	0.41					
503	101.94	1.74					
1012	102.94	2.74					
1505	103.67	3.47					
2005	104.15	3.95					
2403	104.50	4.30					
2508	104.60	4.40					
2711	104.71	4.51					
2800	104.73	4.53					
3000	104.88	4.68					

Test #14

Clamping block position: 2
Strain level: $\pm 4078 \mu\epsilon$
α : .05"
δ : .516"

Cycle	R_g	ΔR	ϵ_N	ϵ_C	ϵ_t	ϵ_T	ϵ_R
0	100.21		719	3618	4447	8065	4033
1	100.10		55	2915	5185	8100	4050
5	100.14		187	2946	5213	8159	4079
6			190	2912	5260	8172	4086
7			233	2906	5252	8158	4079
8			262	2894	5263	8157	4079
9			328	2914	5234	8148	4074
10	100.21	0.0	390	2946	5200	8146	4073
108	100.58	0.37					
502	101.81	1.60					
1008	102.84	2.63					
1506	103.51	3.30					
2016	103.99	3.78					
2203	104.18	3.97					
2503	104.39	4.18					
2809	104.55	4.34					
3003	104.70	4.49					
3109	104.76	4.55					
3171	104.80	4.59					
3250	104.84	4.63					
3350	104.90	4.69					

APPENDIX E

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Also see Appendix E.

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13. ABSTRACT

An investigation is made of the feasibility of the use of the S/N Fatigue Life Gage as a monitoring device for cumulative fatigue damage in 70-30 copper-nickel.

The study is aimed at verifying the hypothesis that the permanent change in resistance experienced by such a gage when bonded to a structure subjected to varying load conditions is a function of the strain history of the underlying material, and that the total resistance change in the gage at the time of crack initiation in the structure is essentially constant, independent of strain level or history.

In particular, because of its importance in naval applications, the material for which this hypothesis has been examined in this study is 70-30 copper-nickel.

The hypothesis is sufficiently well verified to justify recommending testing at additional strain levels, and evaluating the effects of block-cycling, aging and other influences likely to be encountered in in-service monitoring of fatigue damage.

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